Constraints on modified Chaplygin gas from recent observations and a comparison of its status with other models

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In this Letter, a modified Chaplygin gas (MCG) model of unifying dark energy and dark matter with the exotic equation of state $p_{MCG} = B\rho_{MCG} - \frac{A}{\rho^{\alpha}_{MCG}}$ is constrained from recently observed data: the 182 Gold SNe Ia, the 3-year WMAP and the SDSS baryon acoustic peak. It is shown that the best fit value of the three parameters (B,B_s,α) in MCG model are (-0.085,0.822,1.724). Furthermore, we find the best fit $w(z)$ crosses -1 in the past and the present best fit value $w(0) = -1.114 < -1$, and the 1σ confidence level of $w(0)$ is $-0.946 \leq w(0) \leq -1.282$. Finally, we find that the MCG model has the smallest χ^2_{min} value in all eight given models. According to the Alaike Information Criterion (AIC) of model selection, we conclude that recent observational data support the MCG model as well as other popular models.

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I. INTRODUCTION

The type Ia supernova (SNe Ia) explorations [1], the cosmic microwave background(CMB) results from WMAP [2] observations, and surveys of galaxies [3] all suggest that the universe is speeding up rather than slowing down. The accelerated expansion of the present universe is usually attributed to the fact that dark energy is an exotic component with negative pressure. Many kinds of dark energy models have already been constructed such as ΛCDM [4], quintessence [5], phantom [6], generalized Chaplygin gas (GCG) [7], quintom [8], holographic dark energy [9], and so forth.

On the other hand, to remove the dependence of special properties of extra energy components, a parameterized equation of state (EOS) is assumed for dark energy. This is also commonly called the model-independent method. The parameterized EOS of dark energy which is popularly used in parameter best fit estimations, describes the possible evolution of dark energy. For example, $w = w_0$=const [10], $w(z) = w_0 + w_1 z$ [11], $w(z) = w_0 + \frac{w_1 z}{1+z}$ [12], $w(z) = w_0 + \frac{w_1 z}{(1+z)^2}$ [13], $w(z) = \frac{1+z}{3}\frac{A_1+2A_2(1+z)}{X} - 1$ (here $X \equiv A_1(1+z) + A_2(1+z)^2 + (1 - \Omega_{0m} - A_1 - A_2)$) [14]. The parameters w_0, w_1, or A_1, A_2 are obtained by the best fit estimations from cosmic observational datasets.

It is well known that the GCG model has been widely used to interpret the accelerating universe. In the GCG approach, dark energy and dark matter can be unified by using an exotic equation of state. Also, a Modified Chaplygin gas (MCG) as a extension of the generalized Chaplygin gas model has already been applied to describe the current

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accelerating expansion of the universe [15] [16] [17] [18]. The constraint on parameter B in MCG model, i.e., the added parameter relative to GCG model, is discussed briefly by using the location of the peak of the CMB radiation spectrum in Ref. [19]. In this Letter, we study the constraints on the best fit parameters (B, B_s,α) and EOS in the MCG model from recently observed data: the latest observations of the 182 Gold type Ia Supernovae (SNe) [20], the 3-year WMAP CMB shift parameter [21] and the baryon acoustic oscillation (BAO) peak from Sloan Digital Sky Surver (SDSS) [22]. The result of this study indicates that the best fit value of parameters (B, B_s,α) in MCG model are (-0.085,0.822,1.724). Furthermore, we find the best fit $w(z)$ crosses -1 in the past and the present best fit value $w(0) = -1.114 < -1$, and the 1σ confidence level of $w(0)$ is $-0.946 \leq w(0) \leq -1.282$. At last, because the emphasis of the ongoing and forthcoming research is shifting from estimating specific parameters of the cosmological model to model selection [23], it is interesting to estimate which model for an accelerating universe is distinguish by statistical analysis of observational datasets out of a large number of cosmological models. Therefore, by applying the recent observational data to the Alaike Information Criterion (AIC) of model selection, we compare the MCG model with other seven general cosmological models to see which model is better. It is found that the MCG model has almost the same support from the data as other popular models. In the Letter, we perform an estimation of model parameters using a standard minimization procedure based on the maximum likelihood method.

The Letter is organized as follows. In section 2, the MCG model is introduced briefly. In section 3, the best fit value of parameters (B, B_s,α) in the MCG model are given from the recent observations of SNe Ia, CMB and BAO, and we present the evolution of the best fit of $w(z)$ with 1σ confidence level with respect to redshift z. The preferred cosmological model is discussed in section 4 according to the AIC. Section 5 is the conclusion.

II. MODIFIED CHAPLYGIN GAS MODEL

For the modified Chaplygin gas model, the energy density ρ and pressure p are related by the equation of state [15]

$$p_{MCG} = B\rho_{MCG} - \frac{A}{\rho^{\alpha}_{MCG}}, \tag{1}$$

where A, B, and α are parameters in the model.

Considering the FRW cosmology, by using the energy conservation equation: $d(\rho a^3) = -pd(a^3)$, the energy density of MCG can be derived as [18]

$$\rho_{MCG} = \rho_{0MCG}[B_s + (1 - B_s)(1 + z)^{3(1+B)(1+\alpha)}]^{\frac{1}{1+\alpha}}, \tag{2}$$

for A $\neq$ -1, where a is the scale factor, $B_s = \frac{A}{(1+B)\rho_0^{1+\alpha}}$. In order to unify dark matter and dark energy for the MCG model, the MCG fluid is decomposed into two components: the dark energy component and the dark matter component, i.e., $\rho_{MCG} = \rho_{de} + \rho_{dm}$, $p_{MCG} = p_{de}$. Then according to the relation between the density of dark matter and redshift:

$$\rho_{dm} = \rho_{0dm}(1 + z)^3, \tag{3}$$

the energy density of the dark energy in the MCG model can be given by

$$\rho_{de} = \rho_{MCG} - \rho_{dm} = \rho_{0MCG}[B_s + (1 - B_s)(1+z)^{3(1+B)(1+\alpha)}]^{\frac{1}{1+\alpha}} - \rho_{0dm}(1+z)^3. \tag{4}$$

Next, we assume the universe is filled with two components, one is the MCG component, and the other is baryon matter component, ie., $\rho_t = \rho_{MCG} + \rho_b$. The equation of state of dark energy can be derived as [18]

$$w_{de} = \frac{(1-\Omega_{0b})[B_s + (1-B_s)(1+z)^{3(1+B)(1+\alpha)}]^{-\frac{\alpha}{1+\alpha}}[-B_s + B(1-B_s)(1+z)^{3(1+B)(1+\alpha)}]}{(1-\Omega_{0b})[B_s + (1-B_s)(1+z)^{3(1+B)(1+\alpha)}]^{\frac{1}{1+\alpha}} - \Omega_{0dm}(1+z)^3}, \tag{5}$$

where Ω_{0dm} and Ω_{0b} are present values of the dimensionless dark matter density and baryon matter component.

Furthermore, in a flat universe, making use of the Friedmann equation, the Hubble parameter H can be written as

$$H^2 = \frac{8\pi G\rho_t}{3} = H_0^2 E^2, \tag{6}$$

where $E^2 = (1\text{-}\Omega_{0b})[B_s + (1-B_s)(1+z)^{3(1+B)(1+\alpha)}]^{\frac{1}{1+\alpha}} + \Omega_{0b}(1+z)^3$. H_0 denotes the present value of the Hubble parameter. When $B = 0$, equation (6) is reduced to the GCG scenario.

In the following section, on the basis of equation (6), we will apply the recently observed data to find the best fit parameters (Ω_{0b}, B, B_s,α) in MCG model. For simplicity, we will displace parameters (Ω_{0b}, B, B_s,α) with θ in the following section.

III. THE BEST FIT PARAMETERS FROM PRESENT COSMOLOGICAL OBSERVATIONS

Since type Ia Supernovae behave as Excellent Standard Candles, they can be used to directly measure the expansion rate of the universe up to high redshifts ($z \geq 1$) for comparison with the present rate. Therefore, they provide direct information on the universe's acceleration and constrain the dark energy model. Theoretical dark energy model parameters are determined by minimizing the quantity

$$\chi^2_{SNe}(H_0, \theta) = \sum_{i=1}^{N} \frac{(\mu_{obs}(z_i) - \mu_{th}(z_i))^2}{\sigma^2_{obs;i}}, \tag{7}$$

where $N = 182$ for the Gold SNe Ia data [20], $\sigma^2_{obs;i}$ are errors due to flux uncertainties, intrinsic dispersion of SNe Ia absolute magnitude and peculiar velocity dispersion respectively. The theoretical distance modulus μ_{th} is defined as

$$\mu_{th}(z_i) \equiv m_{th}(z_i) - M = 5log_{10}(D_L(z)) + 5log_{10}(\frac{H_0^{-1}}{Mpc}) + 25, \tag{8}$$

where

$$D_L(z) = H_0 d_L(z) = (1+z)\int_0^z \frac{H_0 dz'}{H(z'; H_0, \theta)}, \tag{9}$$

μ_{obs} is given by supernovae dataset, and d_L is the luminosity distance.

The structure of the anisotropies of the cosmic microwave background radiation depends on two eras in cosmology, i.e., last scattering and today. They can also be applied to limit the model parameters of dark energy by using the

shift parameter [24],

$$R = \sqrt{\Omega_{0m}} \int_0^{z_{rec}} \frac{H_0 dz'}{H(z'; H_0, \theta)}, \tag{10}$$

where $z_{rec} = 1089$ is the redshift of recombination, Ω_{0m} is present value of the dimensionless matter density, including dark matter and the baryon matter component. By using the three-year WMAP data [25], R can be obtained as [26]

$$R = 1.71 \pm 0.03. \tag{11}$$

From the CMB constraint, the best fit value of parameters in the dark energy models can be determined by minimizing

$$\chi^2_{CMB}(H_0, \theta) = \frac{(R(H_0, \theta) - 1.71)^2}{0.03^2}. \tag{12}$$

Because the universe has a fraction of baryons, the acoustic oscillations in the relativistic plasma would be imprinted onto the late-time power spectrum of the nonrelativistic matter [27]. Therefore, the acoustic signatures in the large-scale clustering of galaxies can also serve as a test to constrain models of dark energy with detection of a peak in the correlation function of luminous red galaxies in the SDSS [22]. By using the equation

$$A = \sqrt{\Omega_{0m}} E(z_{BAO})^{-1/3} [\frac{1}{z_{BAO}} \int_0^z \frac{H_0 dz'}{H(z'; H_0, \theta)}]^{2/3}, \tag{13}$$

and $A = 0.469 \pm 0.017$ measured from the SDSS data, $z_{BAO} = 0.35$, we can minimize the χ^2_{BAO}defined as [28]

$$\chi^2_{BAO}(H_0, \theta) = \frac{(A(z'; H_0, \theta) - 0.469)^2}{0.017^2}. \tag{14}$$

As one can find that the gravitational clustering in MCG model presented in Ref. [17], ensures that the observational datasets from CMB and BAO can be applied to constrain the MCG model. Hence, we combine these three datasets to minimize the total likelihood χ^2_{total}

$$\chi^2_{total}(H_0, \theta) = \chi^2_{SNe} + \chi^2_{CMB} + \chi^2_{BAO}. \tag{15}$$

On the one hand, since we are interested in the model parameters θ, the H_0 contained in $\chi^2_{total}(H_0, \theta)$ is a nuisance parameter and will be marginalized by integrating the likelihood $L(\theta) = \int dH_0 P(H_0) \exp\ (-\chi^2(H_0, \theta)/2)$, where $P(H_0)$ is the prior distribution function of the present Hubble constant, and a Gaussian prior $H_0 = 72 \pm 8 kmS^{-1}Mpc^{-1}$ [29] is adopted in the Letter. We know that the prior knowledge of cosmological parameter Ω_{0b} has been obtained by several other observations, such as $\Omega_{0b}h^2 = 0.0214 \pm 0.0020$ from the observation of the deuterium to hydrogen ratio towards QSO absorption systems [30], $\Omega_{0b}h^2 = 0.021 \pm 0.003$ from the BOOMERANG data [31] and $\Omega_{0b}h^2 = 0.022^{+0.004}_{-0.003}$ from the DASI results [32] for the observation of CMB. Thus, in order to get the interesting result for the value of Ω_{0b}, we treat Ω_{0b} as a free parameter with Gaussian prior distribution centered in Ω_{0b}^{ture} with spread $\sigma_{\Omega_{0b-prior}}$. And following Ref. [33], the "weak" prior for parameter Ω_{0b} will be used in our analysis, i.e., let it have a relative larger variable range $\Omega_{0b}h^2 = 0.0214 \pm 0.0060$ [33]. Thus, the $\chi^2_{total}(H_0, \theta)$ in equation (15) will be reconstructed as [34]

$$\chi^2_{total-prior}(\theta) = \chi^2_{total}(\theta) + \frac{(\Omega_{0b} - \Omega_{0b}^{true})^2}{\sigma^2_{\Omega_{0b}-prior}}, \tag{16}$$

where $\chi^2_{total}(\theta)$ denotes the total $\chi^2(\theta)$ obtained without imposing prior knowledge of Ω_{0b}.

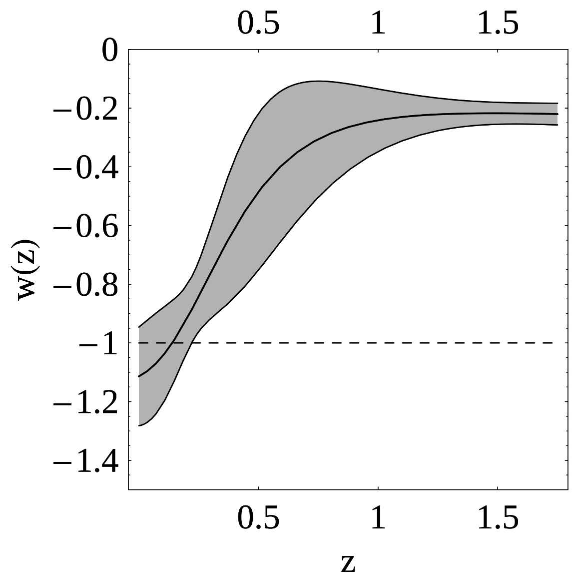

FIG. 1: The best fits of $w(z)$ with 1σ confidence level (shaded region).

By using the maximum likelihood method for equation (16), we obtain the best fit values $(\Omega_{0b}, B, B_s, \alpha)$ in the MCG model (0.041,-0.085,0.822,1.724) with $\chi^2_{min} = 157.272$. Figure 1 shows the 1σ confidence level of the best fit $w(z)$ calculated by using the covariance matrix. From Fig.1, it is easy to see that the best fit $w(z)$ cross -1 at about $z = 0.140$ and the present best fit value $w(0) = -1.114 < -1$. Obviously, it can be shown that the fact that $w(z)$ cross over the boundary of $w = -1$ in MCG model is consistent with the results given by Refs. [14] [35] [36], where $w(z)$ crossing -1 is first found using SNe data. Furthermore, we obtain the 1σ confidence level of $w(0)$, $-0.946 \leq w(0) \leq -1.282$. The possibility of $w(0) > -1$ cann't be excluded in 1σ level. At last, it can be seen that the cosmological constant model (i.e.,$w(z) = -1$) is not in 1σ confidence contour of the best fit dynamical $w(z)$.

IV. THE PREFERRED COSMOLOGICAL MODEL

It is interesting to ask which model of an accelerating universe is preferred by recently observed data over many models. We also want to know how well the MCG model fits the recently observed datasets as compared to other models. We make use of the values of χ^2_{min} and the objective Alaike Information Criterion (AIC) to solve the questions above.

On the basis of the description in section 3, we obtain the values of χ^2_{min} by minimizing the $\chi^2_{total-prior}$ in the corresponding models, where Ω_{0m} is treated as a free parameter with a Gaussian prior in the range $\Omega_{0m} = 0.29 \pm 0.07$ [2] for the ΛCDM model and model-independent cases, and the results are listed in Table 1. It can be seen that the MCG model has the smallest χ^2_{min} value. Table 1 contains the best fit parameters corresponding to the different models.

In cosmology the AIC was first used by Liddle [37], and then in subsequent papers [38] [39]. It is defined as

$$AIC = -2\ln\mathcal{L}(\hat{\theta} \mid data)_{\max} + 2K, \tag{17}$$

where $\mathcal{L}_{max}$ is the highest likelihood in the model with the best fit parameters $\hat{\theta}$, K is the number of estimable

case model	χ^2_{min}	Best fit parameters
ΛCDM	162.302	$\Omega_{0m} = 0.286$
w=constant	159.962	$\Omega_{0m} = 0.288,\ w = -0.870$
$w(z) = w_0 + w_1 z$	159.765	$\Omega_{0m} = 0.292,\ w_0 = -0.893,\ w_1 = 0.009$
$w(z) = w_0 + \frac{w_1 z}{1+z}$	158.635	$\Omega_{0m} = 0.289,\ w_0 = -1.041,\ w_1 = 0.751$
$w(z) = w_0 + \frac{w_1 z}{(1+z)^2}$	157.715	$\Omega_{0m} = 0.282,\ w_0 = -1.314,\ w_1 = 3.059$
$w(z) = \frac{1+z}{3}\frac{A_1+2A_2(1+z)}{X} - 1$	159.067	$\Omega_{0m} = 0.292,\ A_1 = -0.302,\ A_2 = 0.188$
GCG	159.444	$\Omega_{0b} = 0.041,\ A_s = 0.678,\ \alpha = -0.136$
MCG	157.276	$\Omega_{0b} = 0.041,\ B = -0.085,\ B_s = 0.822,\ \alpha = 1.724$

TABLE I: The values of χ^2_{min}, and best fit model parameters against the model

parameters (θ) in the model. The term $-2\ln\mathcal{L}(\hat{\theta} \mid data)$ in Eq.(17) is called χ^2 and it measures the quality of model fit, while the term $2K$ in Eq.(17) interprets model complexity. For more details about AIC please see Refs. [23] [38] [39] [40] [41] .

In what follows, we will estimate which model is the better one for all the models in Table 2. The value of AIC has no meaning by itself for a single model and only the relative value between different models are physically interesting. Therefore, by comparing several models the one which minimizes the AIC is usually considered the best, and denoted by AIC$_{min}$=min$\{$ AIC$_i$, $i = 1, ..., N\}$, where $i = 1, ..., N$ is a set of alternative candidate models. The relative strength of evidence for each model can be obtained by calculating the likelihood of the model $\mathcal{L}(M_i \mid data) \propto$ exp $(-\triangle_i/2)$, where $\triangle_i =$ AIC$_i-$AIC$_{min}$ over the whole range of alternative models. The Akaike weight w_i is calculated by normalizing the relative likelihood to unity and corresponds to posterior probability of a model. The evidence for the models can also be judged by the relative evidence ratio $\frac{w_i}{w_j} = \frac{\mathcal{L}(M_i|data)}{\mathcal{L}(M_j|\text{data})}$. If model i is the best one, the relative evidence ratio gives the odds against the model. The rules for judging the AIC model selections are as follows: when $0 \leq \triangle_i \leq 2$ model i has almost the same support from the data as the best model, for $2 \leq \triangle_i \leq 4$, model i is supported considerably less and with $\triangle_i > 10$ model i is practically irrelevant.

case model	AIC	$\triangle_i$	w_i	Odds
ΛCDM	164.302	0.587	0.149	1.342
w=constant	163.962	0.247	0.177	1.130
$w(z) = w_0 + w_1 z$	165.765	2.050	0.072	2.778
$w(z) = w_0 + \frac{w_1 z}{1+z}$	164.635	0.920	0.126	1.587
$w(z) = w_0 + \frac{w_1 z}{(1+z)^2}$	163.715	0	0.200	1
$w(z) = \frac{1+z}{3}\frac{A_1+2A_2(1+z)}{X} - 1$	165.067	1.352	0.102	1.961
GCG	165.444	1.729	0.084	2.381
MCG	165.276	1.561	0.091	2.198

TABLE II: The value of AIC, Akaike difference, Akaike weights w_i and odds against the model

Thus based on the values of χ^2_{min} of all models in Table 1, the evidence of the AIC can be calculated. We find that the best model is the one following $w(z) = w_0 + \frac{w_1 z}{(1+z)^2}$ in terms of its AIC value. Taking it as a reference, we calculate

the differences between the models by using the AIC differences $\triangle_i$, Akaike weights w_i and odds against alternative models. Table 2 gives the calculating results. Note that the model selection provides quantitative information to judge the "strength of evidence", not just a way to select only one model. From Table 2 it is easy to see that, the MCG model has almost the same support from the data as the best model, because the value of $\triangle_i$ for it is in the range 0-2. Furthermore, it can be shown that the recent observational data supports all of the models in Table 2 except for the case of $w(z) = w_0 + w_1 z$ since the value of $\triangle_i$ for this case is a little bigger than 2. It has a less support from recent observations. On the other hand, we can see that the MCG model is favored by observational data more than GCG model according to the Akaike weights w_i in Table 2. Finally, the odds indicates the difference between MCG model and the best one is 2.198 to 1.

V. CONCLUSION

In summary, the constraints on the MCG model, proposed as a candidate of the unified dark matter-dark energy scenario, has been studied in this Letter. We obtained the best fit value of the three parameters (B,B_s,α) in the MCG model (-0.085,0.822,1.724). Meanwhile, it is easy to see that the best fit $w(z)$ can cross -1 as it evolves with the redshift z, and the present best fit value $w(0) = -1.114 < -1$. Furthermore, it is shown that the 1σ confidence level of $w(0)$ is $-0.946 \leq w(0) \leq -1.282$, and the possibility of $w(0) > -1$ cann't be excluded in 1σ level. We can see that the cosmological constant model (i.e.,$w(z) = -1$) is not in 1σ confidence contour of the best fit dynamical $w(z)$. Finally, in order to find the status of MCG scenario in a large number of cosmological models, we compared the MCG model with other seven popular ones offering explanation of current acceleration of the universe in terms of the values of χ^2_{min} and AIC quantity. We find that, as the quantity χ^2_{min} measures the quality of model fit, the MCG model is preferred by recent observational data because of its a small minimum χ^2 value. On the other hand, it is shown that the MCG model has a slightly high value of AIC due to its many parameters. However, according to the rules of judgment of the AIC model selection, we conclude that recently observed data supports the MCG model as well as other popular models, because the value of $\triangle_i$ for it is in the range 0-2 relative to the best model. In addition, the result of study shows that the recent observational data equivalently supports all of the models in Table 2 except for the case of $w(z) = w_0 + w_1 z$. We expect the new probers such as SNAP and Planck surveyor can provide more accurate data and further explore the nature of dark energy.

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